NRL Report 7932

NTS-1 (TIMATION III) Quartz- and Rubidium-Oscillator Frequency-Stability Results

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This report describes frequency stability results obtained from the NTS-1 satellite. NTS-1 has three on-board frequency sources: one quartz oscillator and two rubidium resonators. These are used to derive the precise time and frequency signals radiated by the spacecraft.

The data taken from each of three 2.5-hr daily passes are time difference (range) or frequency difference (doppler). These data are incorporated into a single value for each pass which is subsequently used in computing long-term Allan-variance results.

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The results presented here employ single-frequency measurements at 335 MHz. Analysis of these results indicate an effect on measured frequency stability that correlates with a resonant term in the orbit. The results further indicate the rubidium frequency depends on the spacecraft temperature, which confirms previous NRL preflight analysis.

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NTS-1 (TIMATION III) QUARTZ- AND RUBIDIUM-OSCILLATOR FREQUENCY-STABILITY RESULTS

INTRODUCTION

The TIMATION (TIMe-navigATION) program originated at NRL in 1964 to demonstrate that a passive ranging technique combined with stable clocks could provide the basis for a satellite navigation system to provide worldwide three-dimensional position determinations and precise time transfer [1, 2]. In 1973 the Navy effort was merged with an Air Force concept into a single program called the NAVSTAR Global Positioning System (GPS). The Air Force was named the executive service, with deputies for each branch of the services.

As a result of these changes the TIMATION-III satellite was redesigned as NTS-1 (Navigation Technology Satellite One) as part of the NAVSTAR GPS effort [3]. The NTS-1 spacecraft was launched on 14 July 1974 into a nominal 8-hour circular orbit. Figure 1a depicts NTS-1 in the transfer-orbit configuration, and Fig. 1b depicts NTS-1 in the final-orbit configuration. Table 1 lists key features of the TIMATION and NTS satellites.

Table 1
TIMATION and Navigation Technology Satellites

Satellite	Launch Date	Altitude (n.mi.)	Inclination (deg)	Eccentricity	Weight (lb)	DC Power (W)	Frequencies	Oscillator	$\Delta F/F$ per Day (parts/10^{13})
T-I	5/31/67	500	70	0.0008	85	6	UHF	Qtz	300
T-II	9/30/69	500	70	0.002	125	18	VHF/UHF	Qtz	100
NTS-1*	7/14/74	7,400	125	0.007	650	100	UHF/L band	Qtz/Rb	5 to 10
NTS-2	9/ ? /76	10,900	63	0	850	300	UHF/L_1/L_2	Cs	2 to 5

*Originally designated TIMATION III.

The NTS-1 has three on-board frequency standards: one quartz oscillator and two rubidium resonators. The quartz oscillator is the primary frequency source for NTS-1, with either one of the two rubidium resonators being activated by ground command. Figure 2 is a block diagram illustrating how the quartz oscillator or either rubidium standard may be selected. Power is always supplied to the quartz oscillator, whereas power may be selectively applied to either one of the rubidium standards (but not both simultaneously).

The quartz oscillator is a Frequency Electonics Company 5-MHz AT-cut fifth-overtone crystal enclosed in a double proportional oven. The oscillator assembly is mounted on a thermoelectric-device (TED) assembly which regulates the oscillator package temperature to a fraction of a degree.

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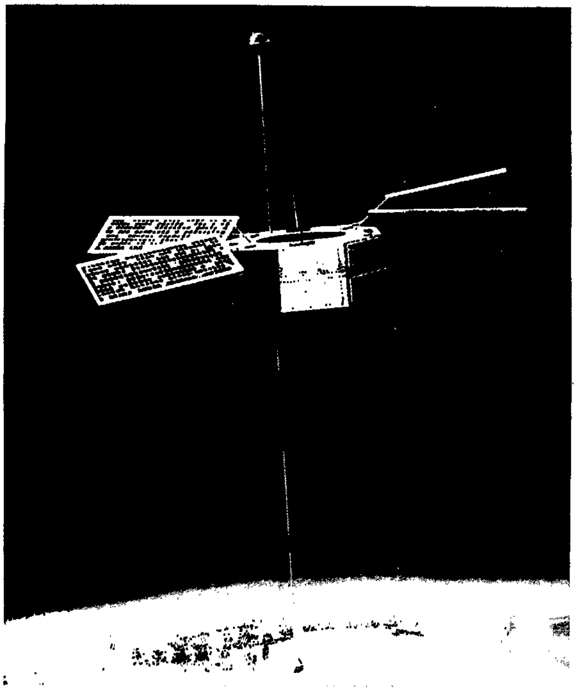
(a) In transfer orbit



(b) In final orbit

Fig. 1 — The NTS-1 satellite

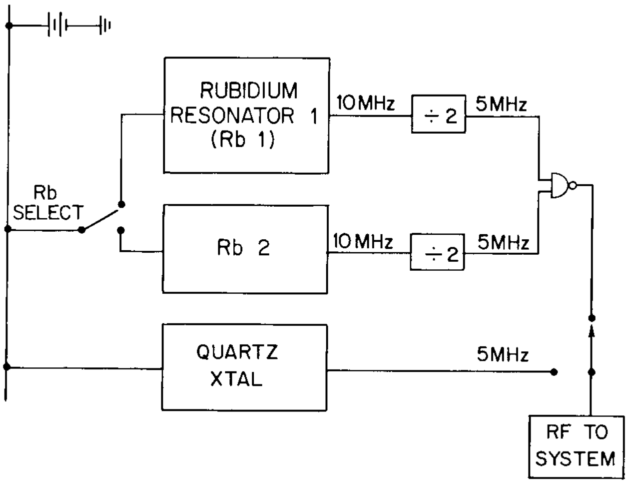


Fig. 2 — Selection of one of the three NTS-1 frequency sources

The two rubidium resonators were built by the Efratom Company. These units were extensively modified by NRL for spacecraft use. Those modifications and the space qualification procedure are described in Ref. 4.

NTS-1 ORBITAL CONSIDERATIONS

The NTS-1 satellite may be tracked for about three passes per day from one station. Figure 3 presents the ground track of NTS-1 for three satellite passes over NRL. NTS-1 is typically over a station for 2.5 hours (9000 seconds). Then the satellite is not observable from that station for about 5 hours. The actual orbital period achieved is slightly less than 8 hours (7 hours 49 minutes), which results in a slight eastward drift of the ground track for each succeeding day. Table 2 presents the NTS-1 orbital parameters for one epoch in 1974.

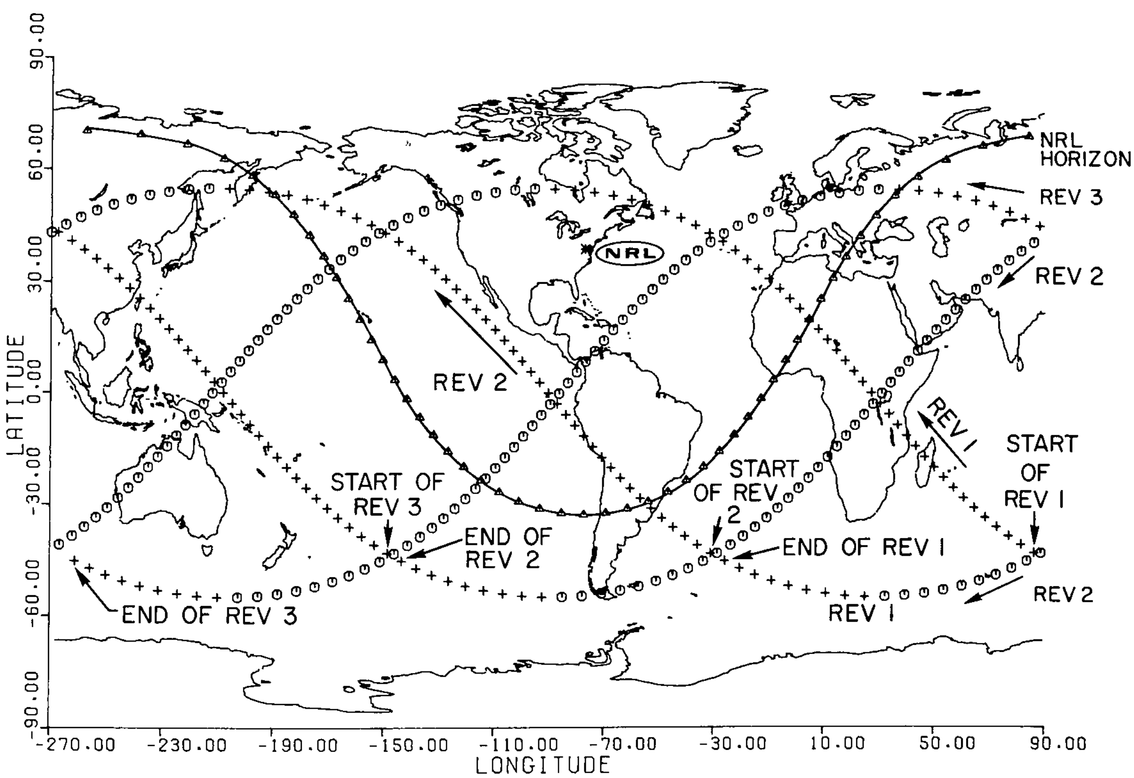


Fig. 3 — NTS-1 ground track for day 262

Table 2
NTS-1 Orbital Elements

Epoch	9/11/74, 21 hr 22.71243 min
Mean motion	3.07212511 rev/day
Height of perigee	7273 n.mi.
Height of apogee	7425 n.mi.
Inclination	125.11 deg
Eccentricity	0.0070
Mean anomaly	294.654 deg
Right ascension	42.5797 deg
Regression	0.11 deg/day
Argument of perigee	66.0739 deg
Rotation of perigee	0.06 deg/day

The orbital configuration places a constraint upon the repetition times that can be used in the Allan-variance calculation. The results presented in this report incorporate the data from a single satellite pass into one number of either time difference or frequency difference. This number is subsequently used in the Allan-variance calculation.

Table 3 shows how the repetition times are obtained from successive revolutions of the satellite. Other pairs than listed in Table 3 may be used, which result in additional repetition times. The shortest repetition time possible with this technique is 0.27 day (23, 000 seconds). The ratio r of the repetition time T to the duration of the sample time τ varies depending on the repetition time used in the calculation.

Table 3
NTS-1 Repetition Times as Calculated by Calculating Differences in Times of Closest Approach

Satellite Revolution	Closest Time of Approach (TCA) (days)	Revolution Pair for which TCA Differences were Determined, Giving Repetition Time	Repetition Time (days)
1	262.124	2 − 1	0.27
2	262.394	3 − 1	0.71
3	262.838	4 − 1	0.98
4	263.104	5 − 1	1.25
5	263.374	6 − 1	1.69
6	263.817	7 − 1	1.96
7	264.085	8 − 1	2.23
8	264.353	9 − 1	2.67
9	264.797	—	—

NTS-1 TRACKING

Currently six stations (Table 4 and Fig. 4) are used for tracking NTS-1. The NRL site is responsible for the command and control of NTS-1 and is further used as a research and development station. The other five stations routinely track NTS-1 with either range (time difference) or doppler (frequency difference) receivers. Each station uses Hewlett-Packard cesium-beam frequency standards as a frequency source for the receivers and associated clocks. The doppler data are sent via the Applied Physics Laboratory Satellite Control Center to the Naval Surface Weapons Center (Dalgren), where the orbit is computed.

Table 4
Coordinates of the NTS-1
Tracking Stations

Station	East Long. (deg)	Geod. Lat. (deg)	Ht. (m)
Seychelles	56	−5	10
Samoa	189	−14	52
Guam	145	14	161
CBD	283	39	31
NRL	283	39	18
Fla.	280	25	23

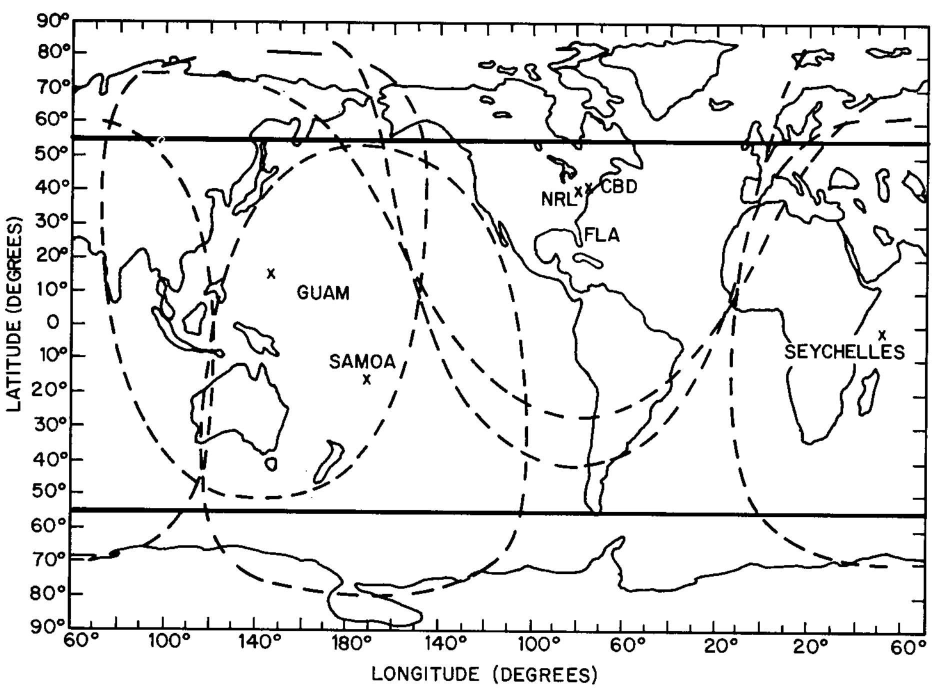


Fig. 4 — NTS-1 tracking stations. The locations and heights are as follows: Guam, 145° E, 14° N, 161 m; Samoa, 189° E, 14° S, 52 m.

TIME-DIFFERENCE MEASUREMENTS

Time differences between the NTS-1 clock and the ground-station clock are measured by means of the side-tone-ranging (STR) equipment. Figure 5 is a graphical model of the time-difference measurement. A sequence of ten side tones at 335 MHz and 1580 MHz are used to measure each time difference. The lowest frequency tone is 100 Hz. Combination of the 100-Hz and 250-Hz measurements yields an effective 50-Hz tone. The highest tone used is 6.4 MHz. The resolution of the system is determined by the 6.4-MHz tone, which yields a resolution of about 1 ns. The tones are on for 7.5 seconds starting at 54.5 seconds after the minute. A coarse measurement of the time difference is obtained from the presence or absence of the ranging-tone waveform, which uniquely resolves the time, as determined by the satellite clock, to approximately 1 ms.

The time-difference measurements can be modeled by the equation

$$O = \frac{\rho}{c} + (t_g - t_{sat}) + \Delta t_{trop} + \Delta t_{iono} + K + \epsilon , \tag{1}$$

where

O = observed time-difference measurement obtained from the time-difference receiver,
ρ = geometric range to the satellite,
c = speed of light,
t_g = time base of the ground-station clock,
t_{sat} = time base of the satellite clock,
Δt_{trop} = time delay due to the troposphere,
Δt_{iono} = time delay due to the ionosphere,
K = delay from the antenna and the receiver,
ϵ = random error in the observation.

Figure 5 shows the correspondence to each term in Eq. (1). The value of ρ to be used in Eq. (1) is not $\rho(t)$ but $\rho[t - \rho\,(t)/c]$, which accounts for the small effect of time aberration.

If the theoretical value of ρ/c is denoted by T, then the clock performance can be determined by analysis of the $(\mathrm{T} - O)$ values, where

$$(\mathrm{T} - O) = \frac{\rho}{c} - O = -(t_g - t_{sat}) - \Delta t_{trop} - \Delta t_{iono} - K - \epsilon . \tag{2}$$

The term T can be defined to include the best estimate of any known term in Eq. (1); however the results presented in this report incorporate into T just the value of ρ/c as obtained from the satellite ephemeris and corrected for time aberration. The value of K, the receiver and antenna delay, can be precisely measured or calibrated to zero. The term Δt_{trop} is usually obtained by the use of a tropospheric delay model. The term Δt_{iono} can be measured if both 335 MHz and 1580 MHz are employed. The term ϵ is treated as the random error, but it can include any unmodeled higher order effects not explicitly given in Eq. (1).

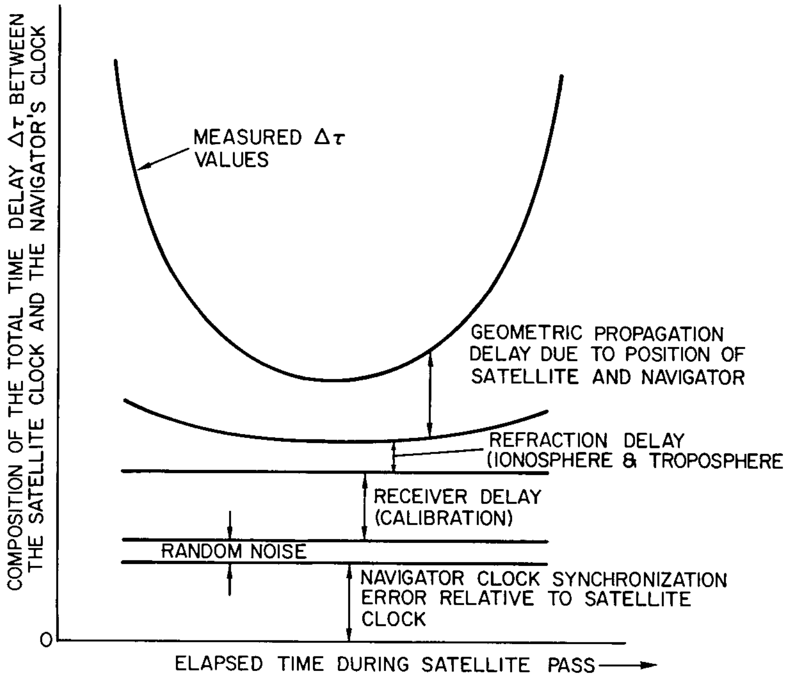


Fig. 5 — Model of the time-difference measurement for NTS-1

Equation (1) does not explicitly contain the frequency difference between the satellite oscillator and the ground-station oscillator. Information on the frequency difference can be obtained by analyzing a sequence of $\{(T - O)_i\}$ values. This can be done in various ways depending on the desired objectives of the analysis. The objective of this report is to obtain relatively long term performance behavior of the satellite oscillators. For this purpose a least-square technique is used which incorporates the initial clock offset at epoch, initial fractional frequency offset at epoch, and aging rate into the state vector. A temperature coefficient is also included where appropriate. The results presented in this report do not assume any a priori knowledge of these parameters; hence the solution obtained is determined completely by the data.

The technique yields 150 measurements of time difference for the 2.5-hour NTS-1 pass. These measurements are used to obtain one value of time difference at the time of closest approach (TCA) of the satellite. A similar procedure is followed for each pass. This information is then used in subsequent calculations to obtain time-difference, frequency, aging-rate, or Allan-variance information.

FREQUENCY-DIFFERENCE MEASUREMENTS

Frequency differences (doppler) between NTS-1 and the ground-station frequency standards are measured by a separate doppler-only receiver built in conjunction with NRL by the Magnavox Company. The received signals at nominal values of 335-MHz and 1580-MHz are scaled to 320 MHz and mixed with a 319.9-MHz signal to produce the scaled doppler with a 100-kHz offset. Then a continuous count for 400 seconds is made with a readout at a nominal 40-second time interval. A 300-second dead time is then observed before the measurement is restarted.

The frequency-difference measurements included in this report are produced as part of the orbit computation. Hence each value of frequency difference represents a smoothed value using typically 75 measurements of doppler obtained during the 9000-second (2.5-hour) pass. The Naval Surface Weapons Center computes the orbit using data from a 3-day span. A typical run includes 30 to 40 passes from all five tracking stations, which are used to simultaneously solve for a frequency offset for each pass and the position and velocity at epoch [5].

ALLAN-VARIANCE COMPUTATION

The Allan-variance calculation requires that four quantities be specified: N is the number of frequency samples, denoted by y, used in each term, T is the repetition interval, τ is the duration of the measurement sample time, and f_h is the system noise bandwidth. The IEEE has recommended that a particular formulation denoted by $\sigma_y^2(t)$ be used:

$$\sigma_y^2(t) = \sigma_y^2(N = 2, T = \tau, \tau, f_h)$$

$$= \left\langle \frac{(\bar{y}_{n+1} - \bar{y}_n)^2}{2} \right\rangle . \quad (3)$$

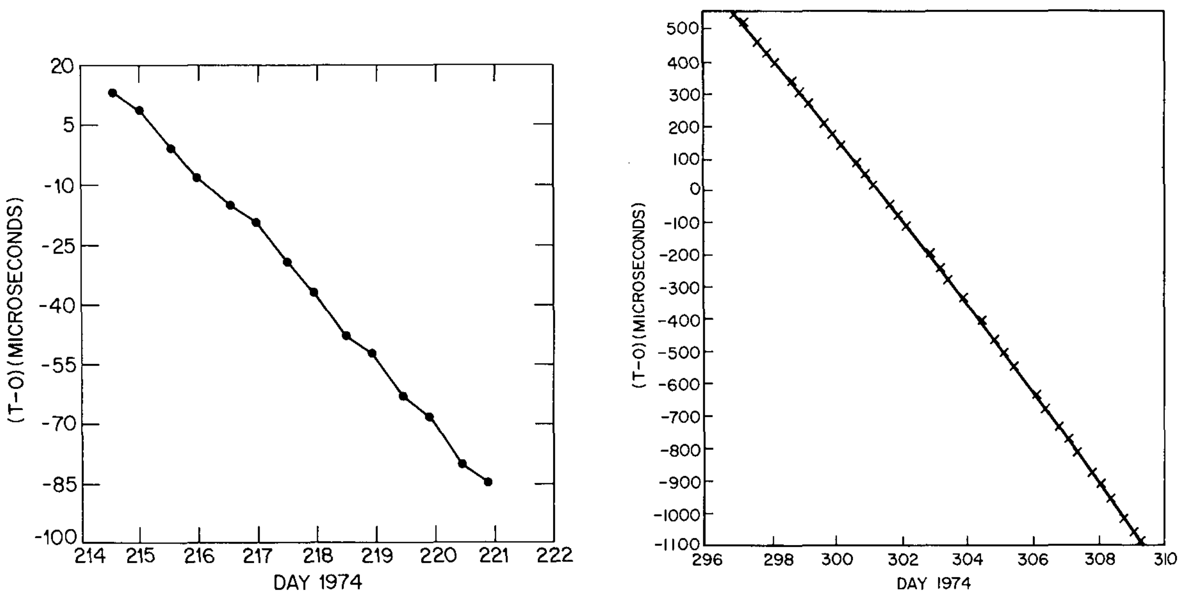
Reference 6 presents a detailed derivation of Eq. (3) and further information on the measurement of frequency stability in the laboratory. The computational form used differs from Eq. (3) only by $T \neq \tau$, and is given by the following equation, where M denotes the number of passes used in the calculation of $\sigma_y^2(t)$:

$$\sigma_y^2(t) \approx \frac{1}{2(M-1)} \sum_{k=1}^{M-1} (\bar{y}_{k+1} - \bar{y}_k)^2 . \quad (4)$$

The Allan-variance results presented in this report use doppler data only; results have been obtained using time-difference data, but those results are not included. The results presented use $N = 2$ (frequency pairs are used). The frequency pairs are not disjoint. For example, if three frequency values ($\bar{y}_1$, $\bar{y}_2$, $\bar{y}_3$) are available, then the frequency pairs ($\bar{y}_2 - \bar{y}_1$) and ($\bar{y}_3 - \bar{y}_2$) are used. This choice results in more samples M in the average than would be obtained by using disjoint pairs. The value of τ that is used is 9000 seconds (2.5 hours). Those values of 40-second doppler that go into the calculation of $\bar{y}_i$ are obtained from all of the doppler measurements that are obtained in a pass. That larger set of measurements is edited to remove spurious data, so that a reliable value of $\bar{y}_i$ may be obtained. The value of f_h is 20 Hz for the doppler receiver. The smallest value for M in the results to be presented is 130; hence the value of $\sigma_{\bar{y}}$ obtained has considerable statistical significance.

QUARTZ-OSCILLATOR RESULTS

Figure 6a is a graph of (T — O) versus time values obtained from the time-difference receiver at the Chesapeake Bay Division of NRL (CBD) shortly after launch. The initial frequency offset observed 20 days after launch (day 195) with respect to the ground-station cesium frequency standard was -1.74×10^{-10} (or -1.74 parts per 10^{10}) with an aging rate of -5.7×10^{-12} per day. Figure 6b presents the (T — O) graph for a 12-day span. The aging rate continued to decrease to a value of -24.9×10^{-12} per day.



(a) Days 214-221: frequency offset (day 215) = -1.74×10^{-10} and aging rate = -5.7×10^{-12} /day

(b) Days 296-308: frequency offset (day 305) = -16.23×10^{-10} and aging rate = -24.9×10^{-12} /day

Fig. 6 — Quartz-oscillator (T — O) versus time as measured by station CBD

Figure 7 is a graph of the frequency offset as measured by all five ground stations. A total of 320 passes are plotted. The average number of points per pass is near 75 for this set of data, which gives nearly 25,000 individual measurements of doppler. These 320 passes were subsequently used to obtain long-term Allan-variance information as presented in Fig. 8. The results indicate a notable decrease in σ_y for repetition times of near 1 day and near 2 days. This phenomena will be discussed further following presentation of the rubidium results.

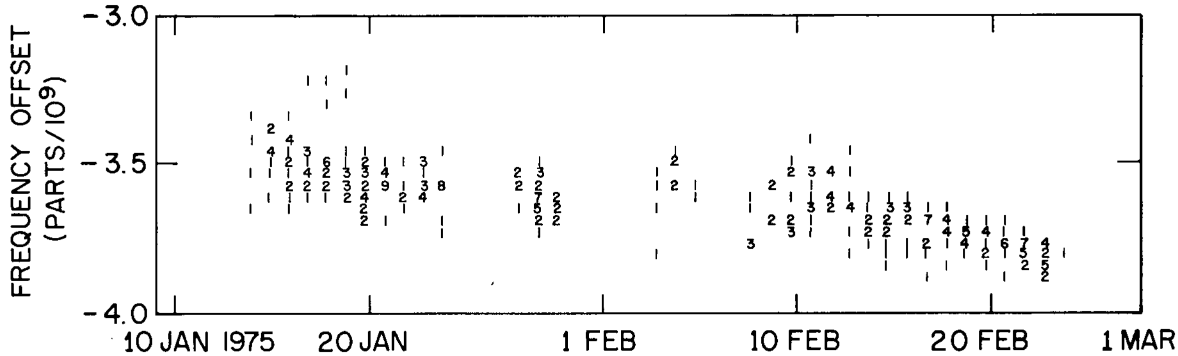


Fig. 7 — Quartz-oscillator doppler frequency for all five stations. The numerals indicate the number of points, where each point represents one pass of the satellite.

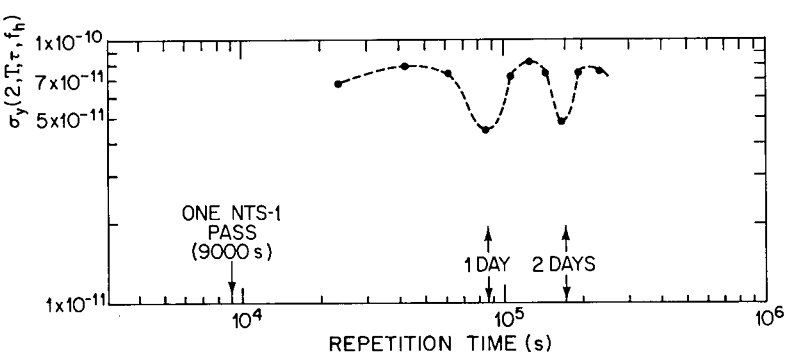


Fig. 8 — Quartz-oscillator Allan variance determined using doppler data from all five stations

Figure 9 presents the deck temperature of the NTS-1 equipment for the first few months in 1975. The maximum value reported here is near 36°C and the minimum is 16°C, which results in a 20°C variation in temperature. Reference to the quartz frequency in Fig. 7 shows that there is no apparent dependence of frequency on temperature. The thermoelectric-device assembly was designed to maintain the quartz oscillator package at 25 ± 0.1°C.

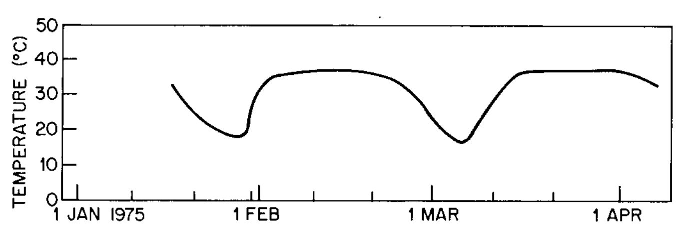
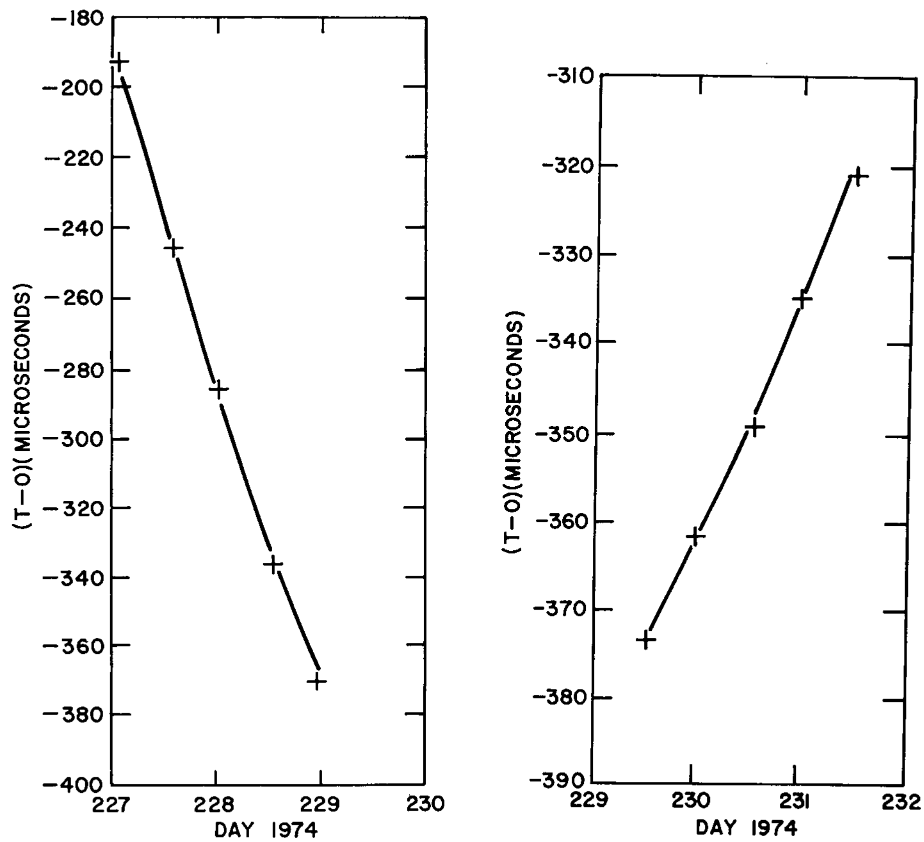


Fig. 9 — Temperature of the NTS-1 equipment deck

RUBIDIUM-RESONATOR-1 (Rb1) RESULTS

Rubidium resonator 1 (Rb1) was activated 1 month after the NTS-1 launch. Control-loop lock occurred within 5 minutes. Figure 10a presents (T — *O*) versus time for a 2-day span. The frequency offset was -10.7×10^{-10}. The high value of aging rate of -15.0×10^{-11}/day was due to the warmup of Rb1. Figure 10b presents (T — *O*) versus time after the C-field tune with a frequency offset of $+4.1 \times 10^{-10}$. The net change was $+14.8 \times 10^{-10}$. A ground-station command for a 26-bit change at 5.15×10^{-11}/bit was issued, resulting in a calculated change of $+13.4 \times 10^{-10}$. The small difference of $+1.4 \times 10^{-10}$ was measured.



(a) Before the magnetic field in the rubidium resonator was used for fine tuning the frequency output (referred to as C-field tune)

(b) After C-field tune

Fig. 10 — Rubidium-resonator-1 (Rb1) (T — *O*) versus time as measured by station CBD

Figure 11 is a plot of control voltage versus time, compared to the equipment-deck-temperature plot of Fig. 9. The control voltage shows two interesting changes. One change is a slow decrease in voltage, which compensates for the aging of the Rb1 quartz crystal. The second change is a dip in control voltage in January and again in early March, obviously correlated with the equipment deck temperature. The measured value of this correlation coefficient for Rb1 is +0.08 volts/°C over the range of 16 to 36°C.

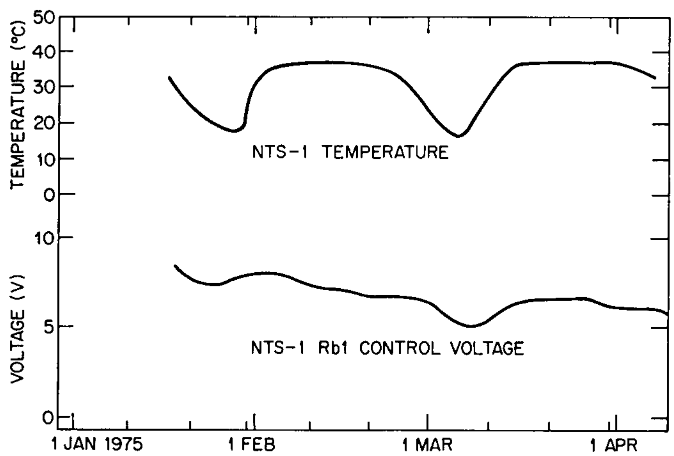


Fig. 11 — Rb1 control voltage, showing correlation with the temperature curve of Fig. 9

Figure 12 presents the frequency offset of Rb1 as a function of time. The data span includes data for 63 days for 415 passes from all five ground stations. Figure 13 is a graph which shows that the Rb1 frequency depends on the equipment deck temperature. Figure 14 presents the residual frequency after solving for initial frequency offset, aging rate, and temperature coefficient. The epoch for this solution was t = 50 days (1975) and the temperature was 30°C. The values obtained were initial frequency offset of 57.2 $\times 10^{-11}$, aging rate of 4.5 $\times 10^{-13}$/day, and temperature coefficient of $-4.2 \times 10^{-11}/°C$. This solution is given by

$$\left(\frac{\Delta F}{F}\right) = [57.2 + 0.045\,(t - 50) - 4.2(\text{temp} - 30)] \times 10^{-11}. \tag{5}$$

The standard errors are 1.0×10^{-11} for initial frequency offset, 0.048×10^{-11}/day for aging rate, and $0.1 \times 10^{-11}/°C$ for the temperature coefficient.

Modifications to the data processing and a signal improvement in NTS-1 resulted in improved data after day 58. Figure 15 presents the Rb1 frequency corrected for temperature using the measured NTS-1 equipment deck temperature and the coefficient of $-4.2 \times 10^{-11}/°C$. Prelaunch measurements of the temperature dependence of the rubidium resonator in a vacuum yielded a coefficient of $-2 \times 10^{-11}/°C$. Analysis of Fig. 15 shows that a sinusoidal signal is present with a period of approximately 2 weeks.

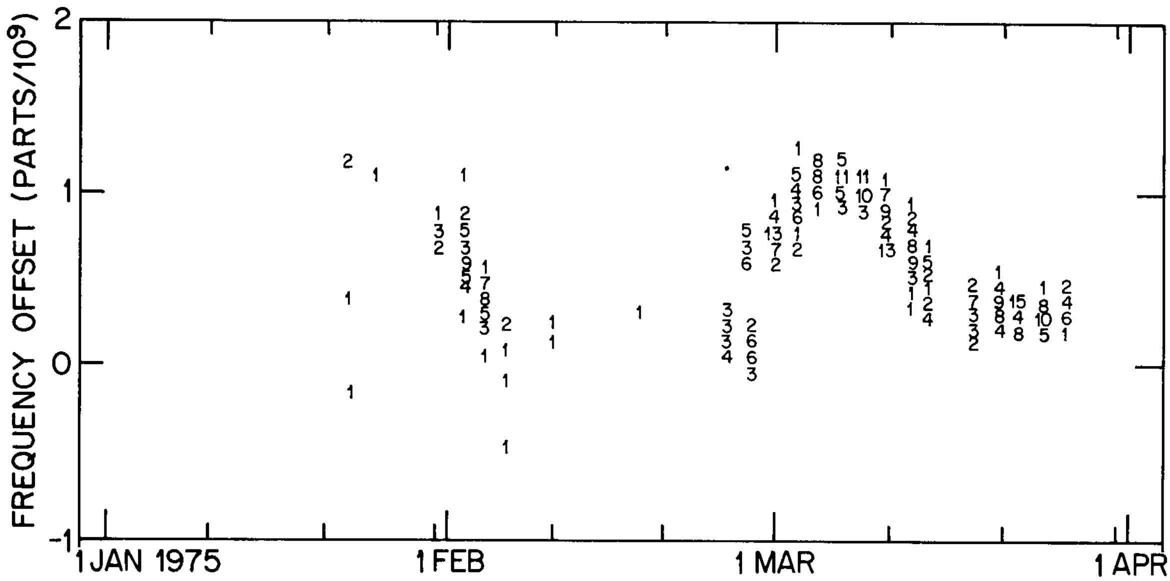


Fig. 12 — Rb1 doppler frequency for all five stations

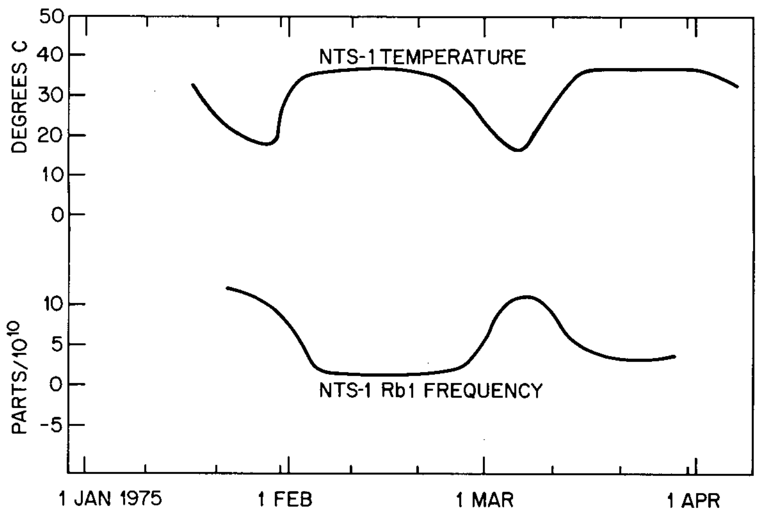


Fig. 13 — Rb1 frequency for all five stations, showing correlation with the temperature curve of Fig. 9

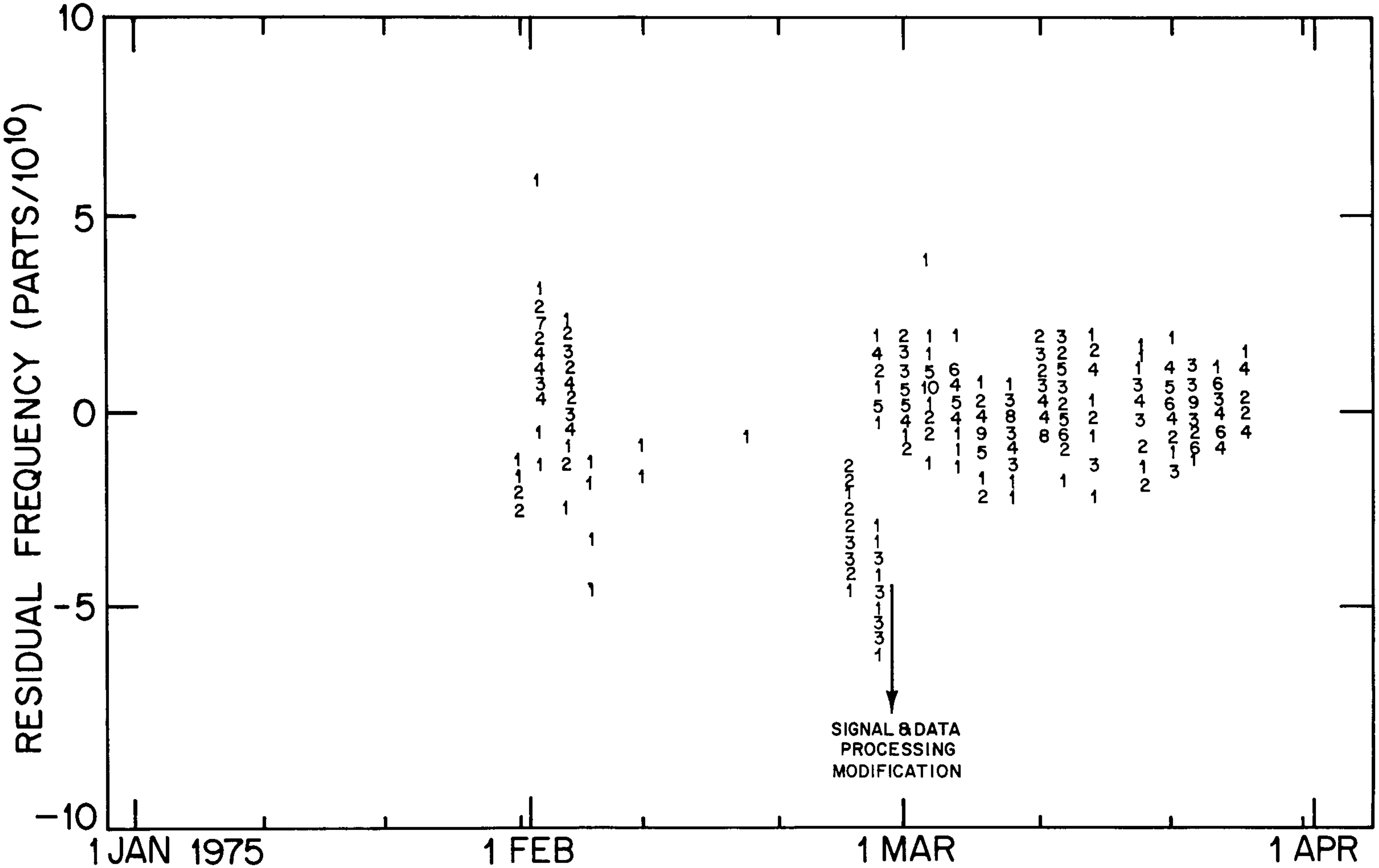


Fig. 14 — Rb1 residual frequency for all five stations

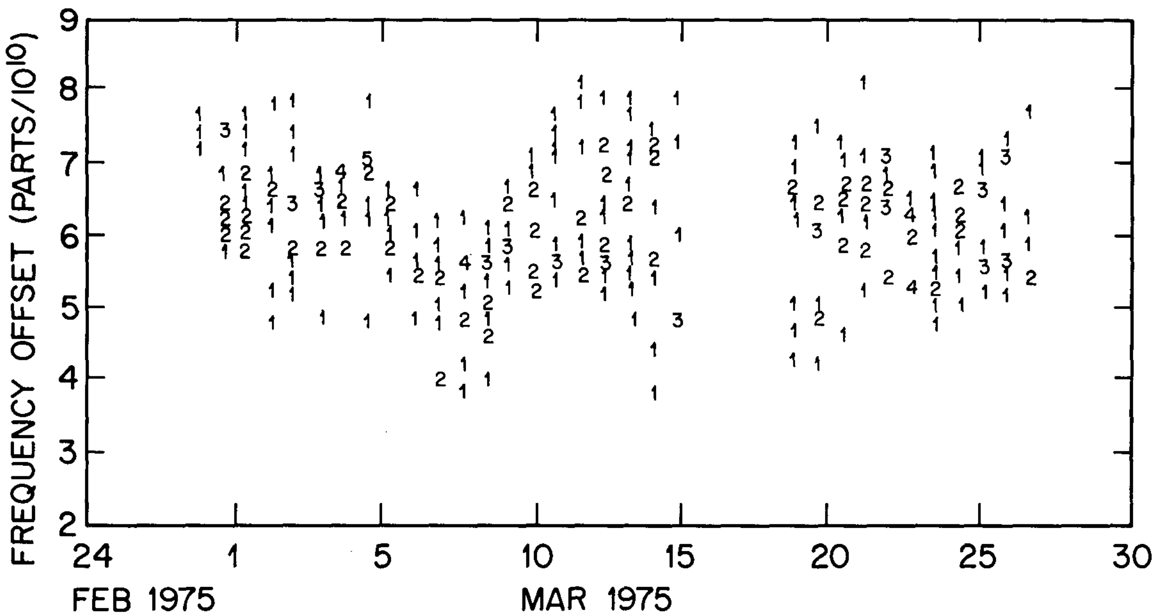


Fig. 15 — Rb1 doppler frequency for all five stations corrected for equipment-deck temperature

Figure 16 presents the measured Allan variance for Rb1. This figure shows a quite similar result to that obtained in Fig. 8 for the quartz oscillator. The shape of both curves was quite unexpected; hence the data were further analyzed to determine the cause of this strange shape.

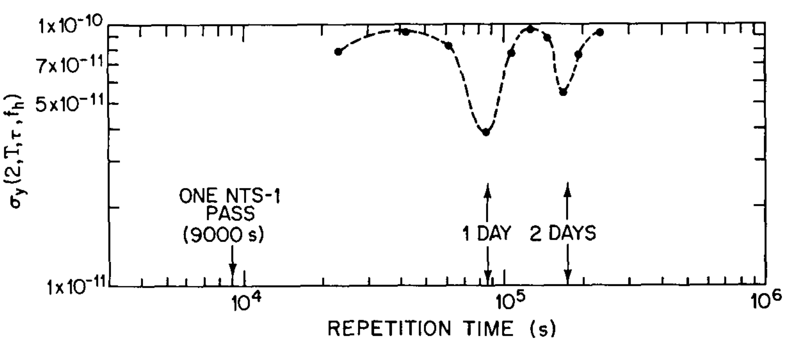
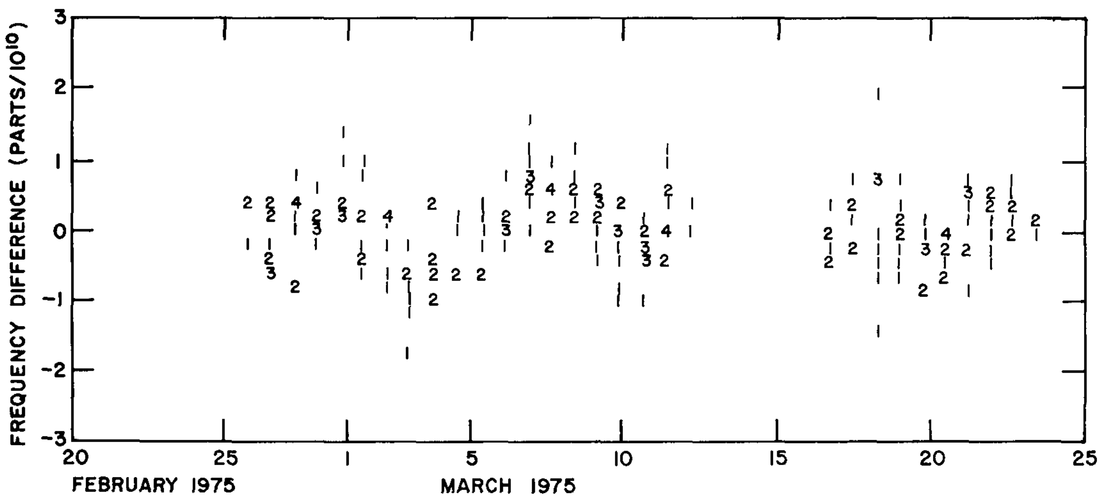
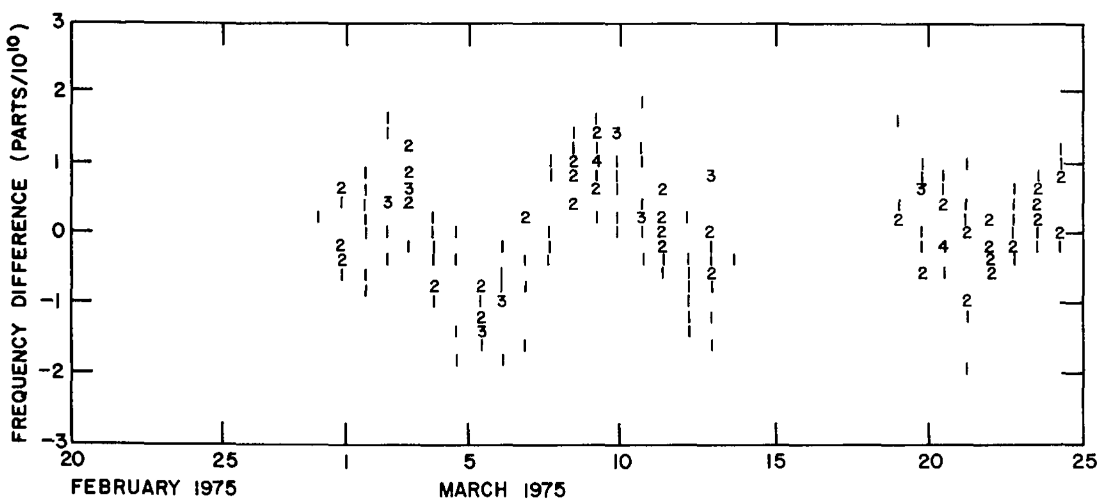


Fig. 16 — Rb1 Allan variance

Figure 17a presents the Rb1 frequency difference $(\bar{y}_{k+1} - \bar{y}_k)$ with a 0.98-day repetition time. Figure 17a shows that a small sinusoidal frequency is present in the data. Figure 17b presents the Rb1 frequency difference $(\bar{y}_{k+1} - \bar{y}_k)$ for a 1.96-day repetition time. A sine wave with a peak variation of approximately 3×10^{-10} and a period near 9 days is present. Figure 17c presents a subset of the Rb1 $(\bar{y}_{k+1} - \bar{y}_k)$ data for station CBD and a 0.48-day repetition time. Detailed examination of the pass times associated with Fig. 17c shows that successive revolutions of NTS-1 0.48 day apart are correlated with $(\bar{y}_{k+1} - \bar{y}_k)$. Figure 18 presents the CBD data of $(\bar{y}_{k+1} - \bar{y}_k)$ for a 0.48-day repetitoin time versus local time. Figure 18 shows that for local time between 02 to 07 hours $(\bar{y}_{k+1} - \bar{y}_k)$ is about equal to -1.5×10^{-10}. For 16 to 20 hours $(\bar{y}_{k+1} - \bar{y}_k)$ is about 1.5 $\times 10^{-10}$, which correlates with the peak variation presented in Fig. 17b. The most probable explanation to the dependence of $(\bar{y}_{k+1} - \bar{y}_k)$ on local time is ionospheric refraction.

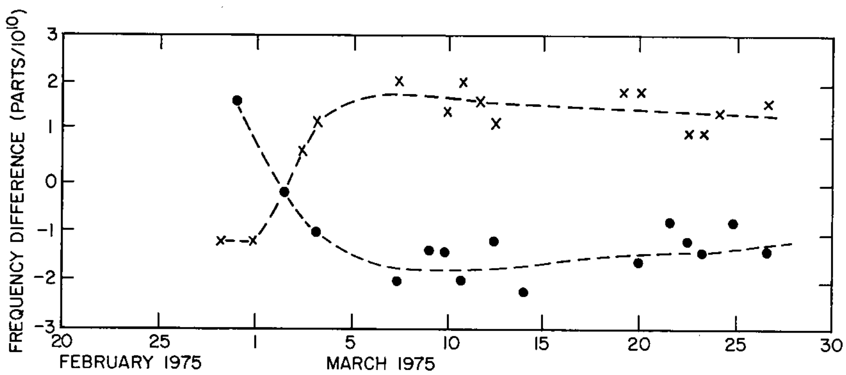


(a) For all five stations and a 0.98-day repetition time ($\sigma_y(t) = 3.9 \times 10^{-11}$)



(b) For all five stations and a 1.96-day repetition time ($\sigma_y(t) = 5.5 \times 10^{-11}$)

Fig. 17 — Rb1 frequency difference $(\bar{y}_{k+1} - \bar{y}_k)$



(c) For station CBD and a 0.48-day repetition time

Fig. 17 (continued)— Rb1 frequency difference ($\bar{y}_{k+1} - \bar{y}_k$)

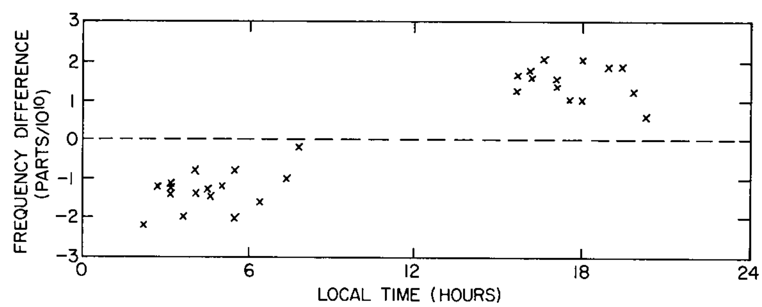


Fig. 18 — Rb1 frequency difference ($\bar{y}_{k+1} - \bar{y}_k$) for station CBD and a 0.48-day repetition time

EFFECTS OF IONOSPHERIC REFRACTION

Figure 19 is a plot of the total electron content in a vertical column versus local time, which will be used to qualitatively explain the behavior of the frequency difference with respect to repetition time. The ionospheric effect on doppler frequency is directly proportional to the rate of change of total electron content along the signal transmission path. Qualitatively, for periods of 1 day the rate of change of total electron content in Fig. 19 are nearly equal, which would account for the minimum value of σ_y in Fig. 8 or 16. For a repetition time of 1/2 day the rate of change of total-electron-content differences show larger variations that do not tend to cancel out. Figure 18 explicitly illustrates this point for a 1/2-day repetition time. Figure 18 further shows the systematic behavior of frequency pairs $\bar{y}_{k+1} - \bar{y}_k$ as a function of the local pass time of the first point $\bar{y}_k$.

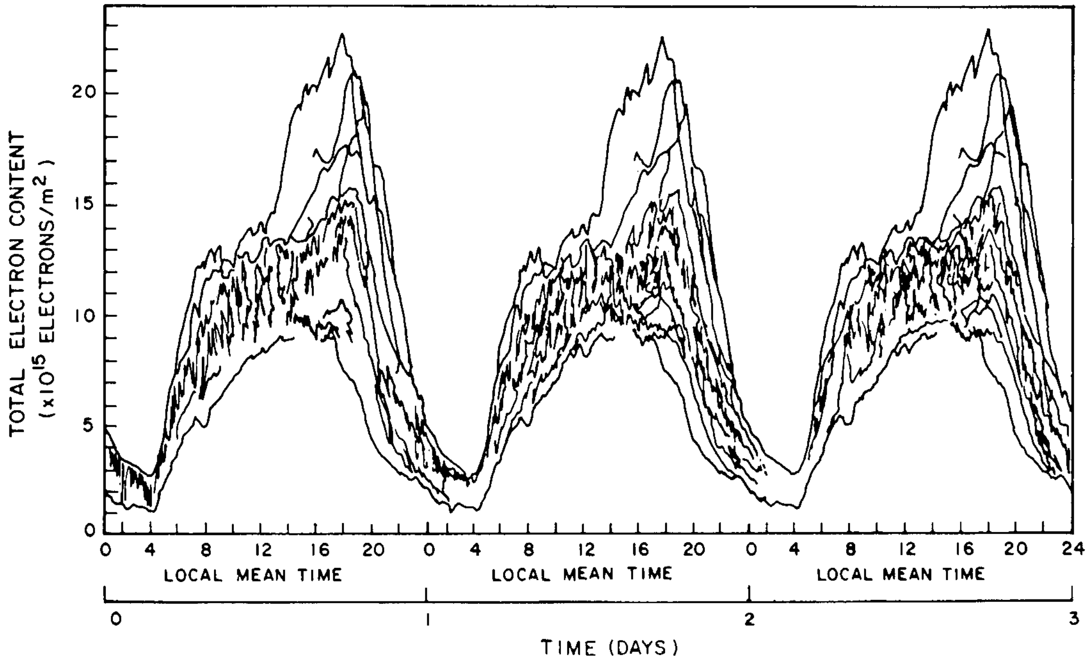
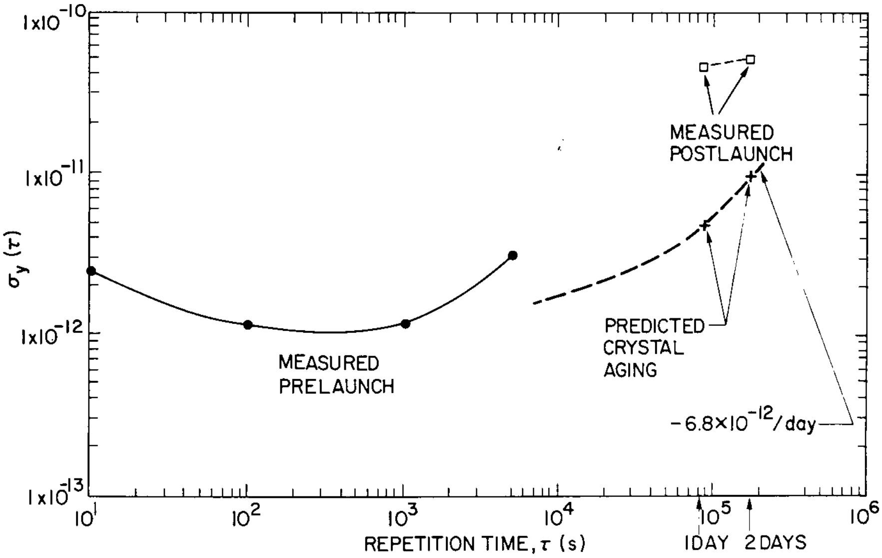


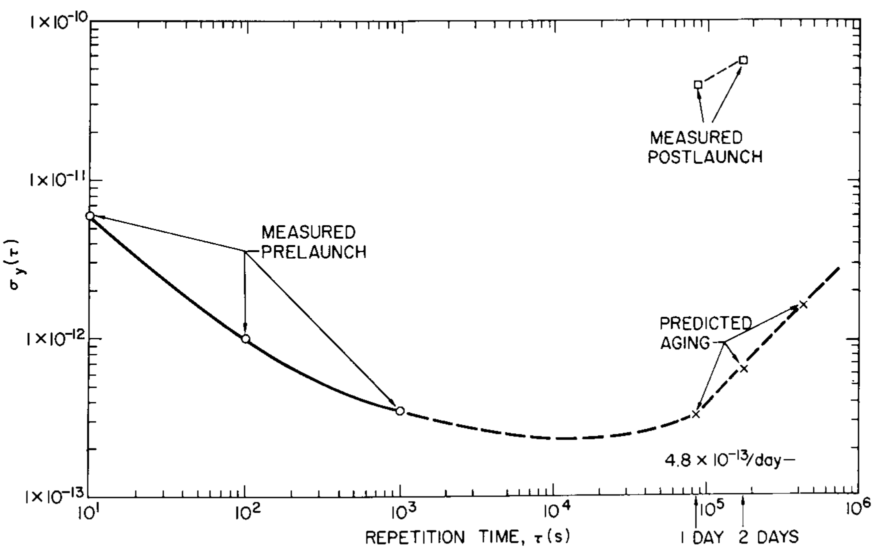
Fig. 19 — Total electron content in 1—m^2 vertical column

Figure 20a presents the prelaunch and postlaunch NTS-1 quartz-oscillator σ_y-versus-repetition-time measurements. The prelaunch data were measured in the laboratory using a system as described in Ref. 7. The postlaunch data were measured through the spacecraft-to-ground link; hence these measurements are influenced by the ionosphere, orbit model, and other factors which are not present in the laboratory measurements. The dashed line indicates the expected value of σ_y as determined by the quartz aging rate which was obtained from Fig. 7. Figure 20b presents the prelaunch and postlaunch NTS-1 Rb1 σ_y measurements. Comparison of Figs. 20a and 20b indicates almost identical values of σ_y for quartz and Rb1 for 1- and 2-day repetition times.

The data presented support the conclusion that the ionospheric refraction has maximum effect on the 335-MHz doppler frequency σ_y values for passes 0.48 day apart and minimum effect for passes with multiple-of-1-day differences. Therefore the values of σ_y presented in Figs. 8 and 16 for 0.98 and 1.96 days represent an upper bound for the NTS-1 quartz and Rb1 frequency-standard performance. Two known systematic effects are present in these measurements: the ionospheric-refraction effect and the long-term orbital-resonance effect. The oscillator performance of the NTS-1 quartz and Rb1 frequency standards is probably considerably better than the σ_y values presented in this report.



(a) Quartz-oscillator measurements



(b) Rb1 measurements

Fig. 20 — Comparison of NTS-1 prelaunch and postlaunch σ_y measurements

CONCLUSIONS

To summarize, the measurements have led to the following conclusions.

- The NTS-1 quartz oscillator has a σ_y value that is less than 4.5×10^{-11} for a 1-day repetition time.

- Rb1 has a measured long-term aging rate of 4.5×10^{-13}/day. The temperature coefficient is $-4.2 \times 10^{-10}/°C$, and a C-field tuning of the rubidium resonator has been executed by the NTS-1 command and control system. The σ_y value for a 1-day repetition time is less than 3.9×10^{-11}.

- A systematic effect on frequency offset using 335-MHz doppler data is present. This effect increases the σ_y values for repetition times of 0.48 day and minimal for 1-day multiples. The most probable cause of this effect is ionospheric refraction.

- A long-term (14-day) effect on frequency offset is present that is probably due to a resonant term in the orbit force model.

- Total measured NTS-1 oscillator performance as presented in this report indicates great dependency on ionospheric measurement. Therefore results described for both rubidium and quartz oscillators are preliminary, and work is continuing to separate total environmental effects from basic oscillator performance specifications.

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